AFRL-HE-BR-TR-2006-0092

EXPLORING VISUAL ADAPTATION AT HIGH INTENSITY LEVELS USING A PULSE-PROBE PARADIGM

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June 2006
Interim Report for July 2005 – June 2006

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
17-06-2006	Interim Technical Report	July 2005 – June 2006

4. TITLE AND SUBTITLE

Exploring Visual Adaptation at High Intensity Levels Using a Pulse-Probe Paradigm

5a. CONTRACT NUMBER
F41624-02-D-7003

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)

Smith; Peter A.; Rogers, Bret Z.; Barnes, Laura E.

5d. PROJECT NUMBER
2312

5e. TASK NUMBER
AH

5f. WORK UNIT NUMBER
03

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Materiel Command
Air Force Research Laboratory
Human Effectiveness Directorate
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Information Technology
4241 Woodcock Drive, Ste B-100
San Antonio, TX 78228-1330

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Materiel Command
Air Force Research Laboratory
Human Effectiveness Directorate
Directed Energy Bioeffects Division
Optical Radiation Branch
Brooks City-Base, TX 78235-5214

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/HEDO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-HE-BR-TR-2006-0092

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited. Other requests for this document shall be referred to AFRL/HEDM, 8262 Hawks Road, Brooks City-Base, TX 78235.

13. SUPPLEMENTARY NOTES

09-12-06: Cleared for public release; PA-06-389 Contract Monitor – Maj Lawrence Schad

14. ABSTRACT

This report describes four experiments in which the temporal changes in visual adaptation that occur during exposure to a train of brief, high intensity discrete light pulses (over 8 log trolands) were explored using a pulse-probe paradigm. For this, the threshold for detecting a probe light stimulus was measured at various latencies with respect to a discretely modulated (pulse) background. Experiments I and II used a 10 ms probe, and explored forward and backward masking for repetitive pulse trains (3 Hz and 10 Hz) and for single pulses. Experiments III and IV also used 3 Hz and 10 Hz pulse trains, but varied the duration of the probe stimulus. The results indicate that asymmetries in the dynamics of forward and backward masking are evident at high intensity levels, that pulse trains induce a DC shift in light adaptation mechanisms, and that stimuli presented during the backward masking window can still contribute to the detection process.

15. SUBJECT TERMS

pulse-probe, light adaptation, temporal dynamics, flicker

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Peter A. Smith
Unclassified	Unclassified	Unclassified	SAR	22	19b. TELEPHONE NUMBER *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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1. INTRODUCTION

The human visual system is capable of maintaining sensitivity in an environment where the ambient light level can varies over eight orders of magnitude – from a dark, moonless night to a bright sunny day. The processes whereby this is achieved are called light and dark adaptation, and these processes occur both in the retina itself, and at higher levels in the visual cortex.

Temporal processes for light and dark adaptation have been extensively studied using psychophysical and physiological techniques (see Hood and Finkelstein[1] for a review) and models of adaptation dynamics have been developed.[2-4] Psychophysical studies of the temporal dynamics of light adaptation have used a probe-sinewave paradigm, where the threshold for detecting a brief pulse (the probe) is measured at various phases on a background that is modulated sinusoidally in time.[5] Our interest is in the effect of pulsed high-intensity periodic backgrounds, and the effect these have on thresholds in between the periodic pulses. To study this we have modified the probe-sinewave paradigm and made measurements of thresholds for detecting probe stimuli presented between the flashes generated by a brief train of light pulses*. Moreover, where previous studies have collected data at up to 10^3 td, we have utilized state-of-the art high-intensity white light emitting diodes to enable measurements at adapting intensities up to five orders of magnitude higher than this (10^8 td).

* We have followed the convention of Bartley[6], who defined the physical stimulus as a *pulse*, and the visual experience a *flash*.

2. METHODS

2.1 Apparatus

The experiments were performed on a purpose-built, dual channel Maxwellian view light stimulator system[7]. The stimulator utilizes state-of-the-art high-brightness white light emitting diodes (LEDs)[8] as light sources and incorporates two channels of visual stimulation: one channel is used to provide an adapting pulse field and a steady background field, while the other channel is the superimposed probe stimulus field. Both channels are presented in Maxwellian view along the same optical axis, and have variable field sizes from around 0.5 to 10°. The stimulator includes a photo-feedback control to monitor diode performance and linearity.

A diagram of the optical layout is provided in Figure 1. The light output from the two Luxeon white LEDs (LXHL-LW5C) is collimated, spatially filtered using apertures, and combined in a cube combiner. The image of the combined apertures is viewed by the subject through the wide field ocular. Changing the size of the aperture thus changes the angular subtense of each channel. The cube combiner transmits 50% of LED channel 1, and reflects 50% of LED channel 2 to the ocular. Conversely, the cube combiner reflects 50% of LED Channel 1, and transmits 50% of LED Channel 2 to the photodiode for monitoring and calibration purposes.

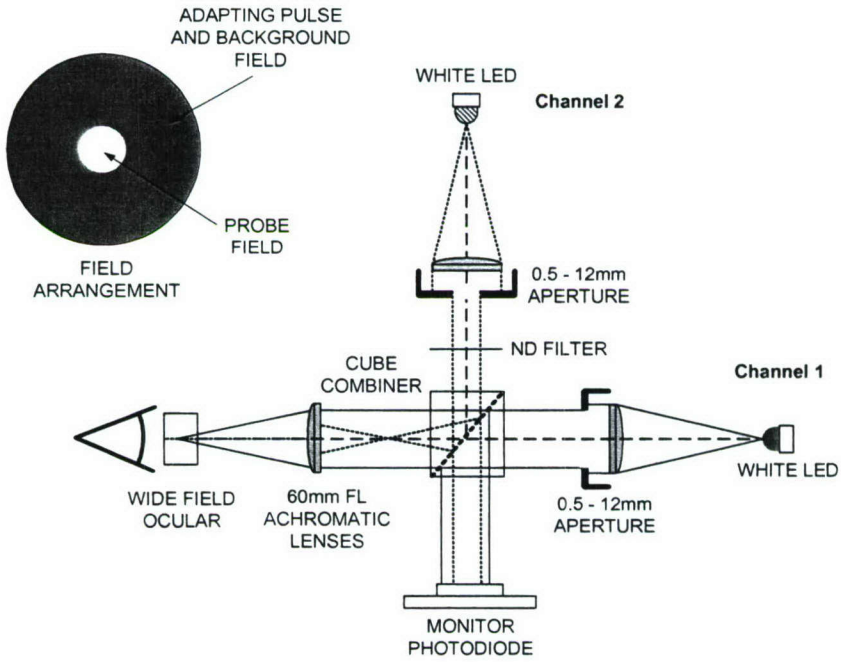

Figure 1. Optical layout of the stimulator system

The intensity of the LEDs was controlled using a pulse density modulation technique.[9] The frequency of fixed current 2 μs pulses[†] from the LEDs was varied from between 100 Hz and 40 kHz by a voltage-to-frequency converter driven through a 16 bit digital-to-analog converter card (National Instruments) in a Dell PC. The system was calibrated by measuring

[†] Note that intensity of the adapting pulse and the probe stimulus were controlled by adjusting the frequency of these 2 μs pulses

the light output from each channel as a function of the digital value from the PC, and this was used in a look-up table to compensate for any non-linearities in the system. Coarse adjustment of the dynamic range of the channels was provided by the insertion of calibrated neutral density filters in the optical train. The retinal illumination was measured using the technique described by Nygaard and Frumkes.[10]

The field homogeneity was measured with a laser beam profiler (Spiricon) and was uniform to within 5%. The spectral emission characteristics of the LEDs were measured with a spectroradiometer (Ocean Optics) throughout the pulse density range and the variation was less than 1%. The LEDs had emission peaks at 450 nm and 550 nm, and a color temperature of 5500 K.

2.2 Observers

Two male observers 45 and 23 years of age participated in this study. They had no known color defects, no paracentral scotomas, and normal dilated fundus examinations. Their uncorrected Snellen acuities were 20/20. Both were experienced psychophysical observers, and they participated in a number of practice sessions before the start of formal data collection. The voluntary informed consent of the observers was obtained as required by Air Force Instruction 40-402.[11]

2.3 Stimuli

The top-left graphic in Figure 1 shows the field arrangement used in these experiments. The background and adapting pulse field was generated by the same LED channel and subtended 10° of visual angle, while the central (probe) field subtended 2 ° of visual angle. Thin wires protruding just into the edge of the aperture were used to help maintain fixation and accommodation.

The probe was always an increment in intensity with respect to the background field. The precise sequence of pulse and probe events depended on the type of experiment (see later), but typically consisted of exposure to a brief luminance increment pulse or train of pulses from the background field. The threshold was then determined for a stimulus presented as a brief luminance increment for the probe field at a fixed delay after each adapting pulse (Figure 2).

2.4 Psychophysical procedure

For each trial the background field luminance was initially set to a fixed level and the observer aligned themselves with the optical apparatus. They were then allowed two minutes to adapt to the background intensity that was presented prior to, in between, and after, the adapting pulses. A pulse-probe sequence was presented, and at the end of the sequence, a brief tone sounded. The observer was then required to respond by pressing a response button if they detected the probe stimulus, which was always present. Test sequences consisted of either a train of pulse-probe stimuli or a single pulse-probe pair. Threshold for the detection of the probe stimulus were determined by a QUEST procedure[12], and a maximum likelihood threshold estimate was determined after 20 test sequences. The delay between test sequences was 1 s, during which the background intensity remained on.

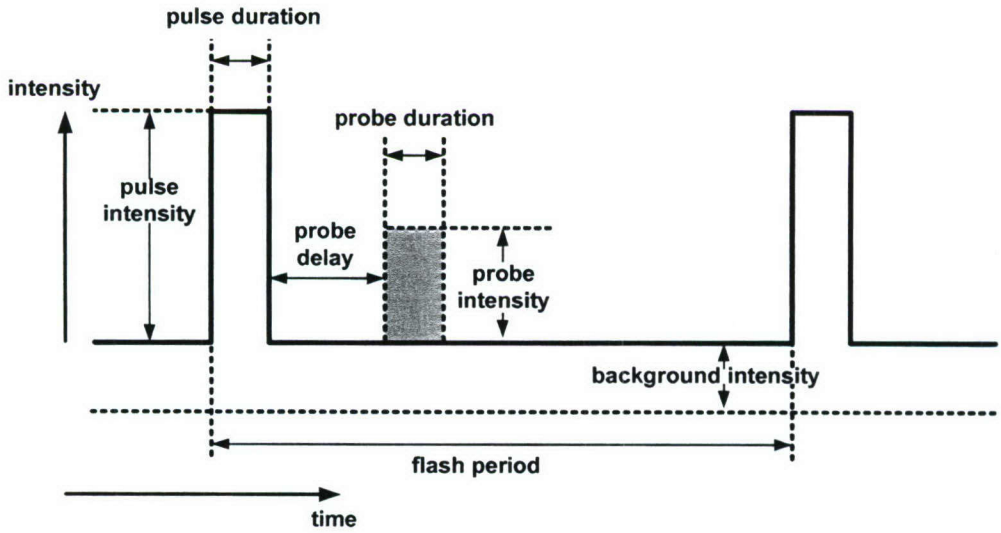

Figure 2. Schematic diagram of typical temporal luminance profiles of adapting pulse and probe stimuli.

2.5 Experiment I: Multiple Pulse-Probe

The first experiment used short, 3 s duration trains of adapting pulses at either 3 Hz or 10 Hz. The duration of the adapting pulses was either 1 ms or 10 ms. The average energy in the adapting pulses was held constant at 8.52×10^5 td-s by adjusting the pulse intensity for each train (Table 1).

Table 1. Adapting pulse parameters for Experiment I.

Frequency (Hz)	Duration (ms)	Intensity (td)	Energy (td-s)
3	1	2.84×10^8	2.84×10^5
3	10	2.84×10^7	2.84×10^5
10	1	8.52×10^7	8.52×10^4
10	10	8.52×10^6	8.52×10^4

During each 3-s pulse-probe sequence, probe stimuli (10 ms duration) were presented at a fixed delay with regard to the adapting pulses (Figure 3, solid arrow), and the observer responded as to whether they detected the probe stimulus at the end of the sequence. The threshold intensity for detection of the probe stimulus (Figure 3, dashed arrow) was determined for a given delay, and thresholds were determined in this way for a range of different delays.

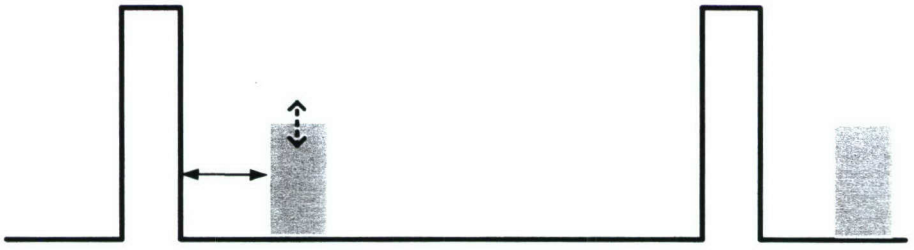

Figure 3. Experiment I: Multiple Pulse-Probe Sequence. The independent variable was the probe delay (solid arrow), the dependent variable was the probe intensity (dotted arrow).

Thresholds for detection of the probe stimulus trains alone (i.e. with no adapting pulses), were also measured at 3 Hz and 10 Hz against a background intensity equal to the time averaged intensity of the adapting pulses (8.52×10^5 td) and the background level presented between the adapting pulses (6.0×10^4 td).

2.6 Experiment II: Single Pulse-Probe

The second experiment measured detection thresholds following exposure to single pulses of the same intensity as those used in the 3 Hz and 10 Hz, 10 ms pulse trains used in Experiment I (i.e. 2.84×10^7 td and 8.52×10^6 td). After the pulse, a single probe stimulus (10 ms duration) was presented at a fixed delay with regard to the adapting pulse (Figure 4, solid arrow). The observer was allowed 1 s after the probe stimulus to respond as to whether they detected the stimulus in the pulse-probe pair. The threshold intensity for detection of the probe stimulus (Figure 4, dotted arrow) was determined for a range of delays between the offset of the adapting pulse and the onset of the probe stimulus.

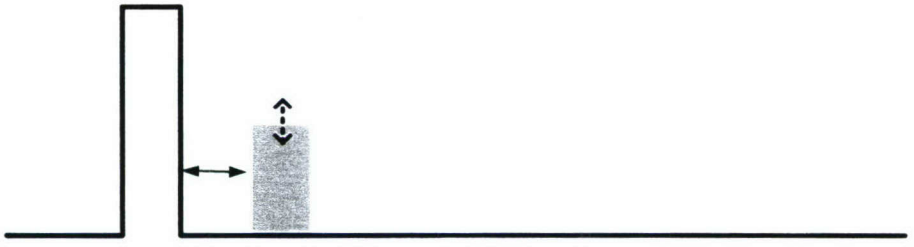

Figure 4. Experiment II: Single Pulse-Probe sequence. The independent variable was the probe delay (solid arrow), the dependent variable was the probe intensity (dotted arrow).

As a control, the threshold for detection of a single probe stimulus against a background intensity of 6.0×10^4 td with no adapting pulse was also determined.

2.7 Experiment III: Single Pulse, Stretched Probe

For this experiment, the adapting pulse trains used in Experiment III were replaced by a single pulse of the same intensity and duration as one of the pulses in the train. After each pulse, a single probe stimulus was presented with no delay between the onset of the probe stimuli and the offset of the adapting pulse, and the observer was allowed 1 s to respond as to

whether they detected the probe stimulus. The threshold intensity for detection of the probe stimulus (Figure 5, dotted arrow) was determined for various probe durations (Figure 5, solid arrow).

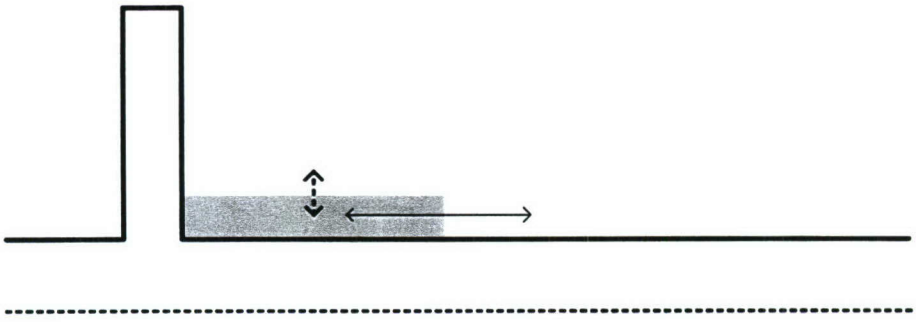

Figure 5. Experiment III: Single Pulse-Stretched Probe sequence. The independent variable was the probe duration (solid arrow), the dependent variable was the probe intensity (dotted arrow).

As a control, thresholds for detection of single stretched probe stimuli against the pre-and post-pulse background intensity of 6.0×10^4 td were also determined for various probe durations.

2.8 Experiment IV: Multiple Pulse-Stretched Probe

The third experiment used the same adapting pulse trains as those in Experiment I. During the pulse train, probe stimuli were presented with no delay between the onset of the probe stimuli and the offset of the adapting pulses. The observer responded as to whether they detected the probe stimuli at the end of each 3 s sequence. The threshold intensity for detection of the probe stimulus (Figure 6, dotted arrow) was determined for various probe durations (Figure 6, solid arrow).

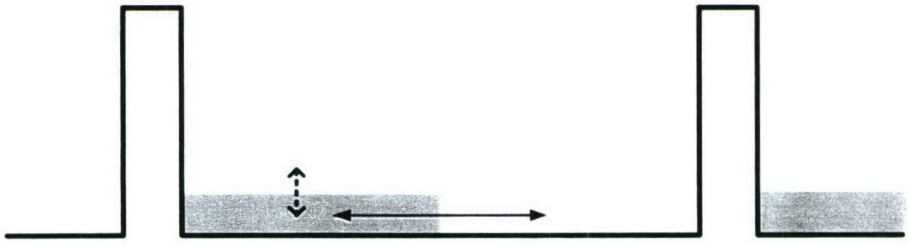

Figure 6. Experiment IV: Multiple Pulse-Stretched Probe sequence. The independent variable was the probe duration (solid arrow), the dependent variable was the probe intensity (dotted arrow).

3. RESULTS

3.1 Experiment I: Multiple Pulse-Probe

The threshold intensity for detection of the probe stimuli is presented as a function of the probe delay for the 3 Hz adapting pulse trains in Figure 7 and for the 10 Hz adapting pulse trains in Figure 8. The triangles are threshold data for 1 ms adapting pulses, while the squares are for 10 ms adapting pulses (means of two observers). Thresholds for detection of the probe stimulus trains alone are shown as horizontal lines. The upper (dotted) line represents measurements made with the background intensity equal to the time average intensity of the adapting pulses (8.52×10^5 td); the lower (dashed) line represents measurements made with the background intensity set equal to that presented in between the adapting pulses in the pulse trains (6.0×10^4 td).

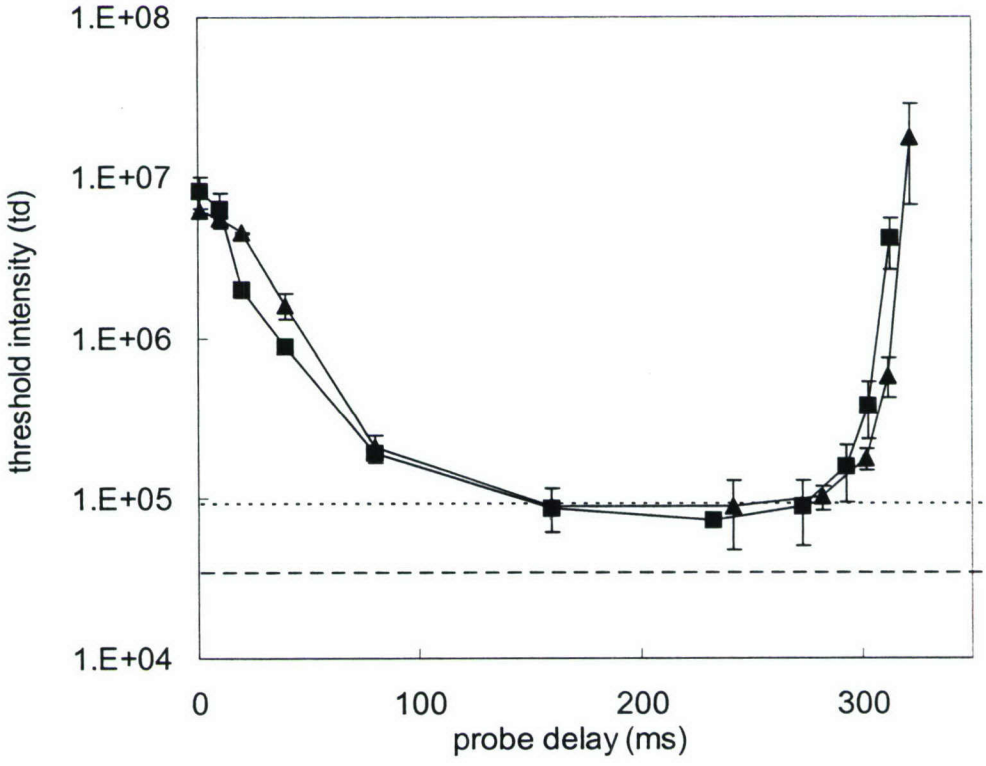

Figure 7. Experiment I: Multiple pulse-probe (3 Hz). Threshold intensity for detection of the probe stimulus as a function of probe delay for 3 Hz equal energy adapting pulses of 1 ms (triangles) and 10 ms (squares) duration. Data points are the means of two observers ± sem. The horizontal lines represent detection threshold for the probe stimulus alone at 3 Hz when the background intensity is equal to the time averaged intensity of the adapting pulses (8.52×10^5 td: dotted line) and the background intensity between the adapting pulses (6.0×10^4 td; dashed line).

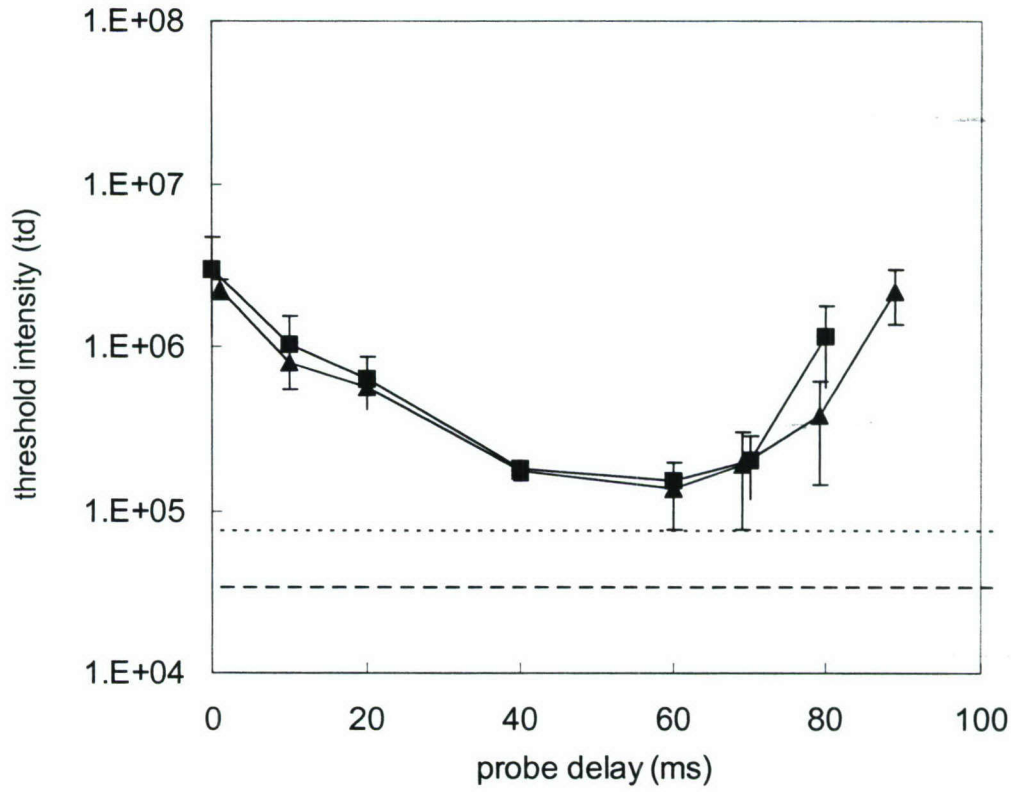

Figure 8. Experiment I: Multiple pulse-probe (10 Hz). Threshold intensity for detection of the probe stimulus as a function of probe delay for 10 Hz equal energy adapting pulses of 1 ms (triangles) and 10 ms (squares) duration. The horizontal lines represent detection threshold for the probe stimulus alone at 10 Hz when the background intensity is equal to the time averaged intensity of the adapting pulses (8.52×10^5 td: dotted line) and the background intensity between the adapting pulses (6.0×10^4 td; dashed line).

3.2 Experiment II: Single Pulse-Probe

The threshold intensity for detection of the single probe stimuli after 10 ms adapting pulses is presented as a function of the probe delay in Figure 9. The solid diamonds are threshold data for 10 ms adapting pulses of 2.84×107 td, while the solid circles are threshold data for adapting pulses of 8.52×106 td (means of two observers). These adapting pulses are the same intensity as those used in the 3 Hz and 10 Hz, 10 ms pulse trains used in the previous experiment. For comparison, the open symbols are the data from the descending portion of Experiment I for 10 ms adapting pulses at 3 Hz (diamonds) and 10 Hz (circles). The threshold for detection of the probe stimulus alone is shown as a horizontal dashed line.

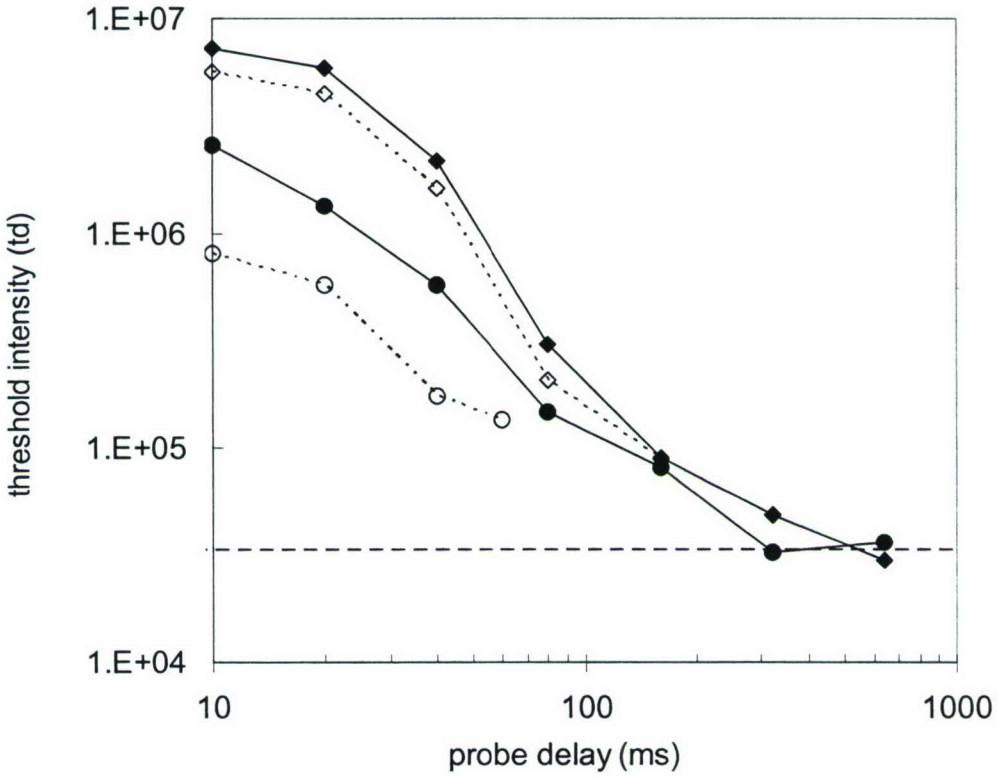

Figure 9. Experiment I: Single pulse-probe. Threshold intensity for detection of single probe stimuli as a function of probe delay for two adapting pulse intensities (2.84×10^7 td - solid diamonds, 8.52×10^6 td - solid circles). The pulses were 10 ms duration. The open symbols are the data from the descending portion of the multiple pulse-probe experiment for 10 ms adapting pulses at 3 Hz (diamonds) and 10 Hz (circles). Data points are the means of two observers. The horizontal line represents the detection threshold for the probe stimulus alone against a background level of 6.0×10^4 td (dashed line).

3.3 Experiment III Single Pulse-Stretched Probe

The threshold intensity for detection of the single pulse-stretched probe stimuli after 10 ms adapting pulses is presented as a function of the probe duration in Figure 10. The solid diamonds are threshold data for adapting pulses of 2.84×10^7 td, while the solid circles are threshold data for adapting pulses of 8.52×10^6 td (means of two observers). The open symbols are the data from the single pulse-probe experiment (Experiment II) for 10 ms adapting pulses at 3 Hz (diamonds) and 10 Hz (circles). Control thresholds for detection of the stretched probe stimulus against a background level equal to the level between the adapting pulses (6.0×10^4 td) are also shown (solid squares) - the line joining these points is the best fit linear regression line to the log-log data and has a slope of -0.47 ($R^2 = 0.97$).

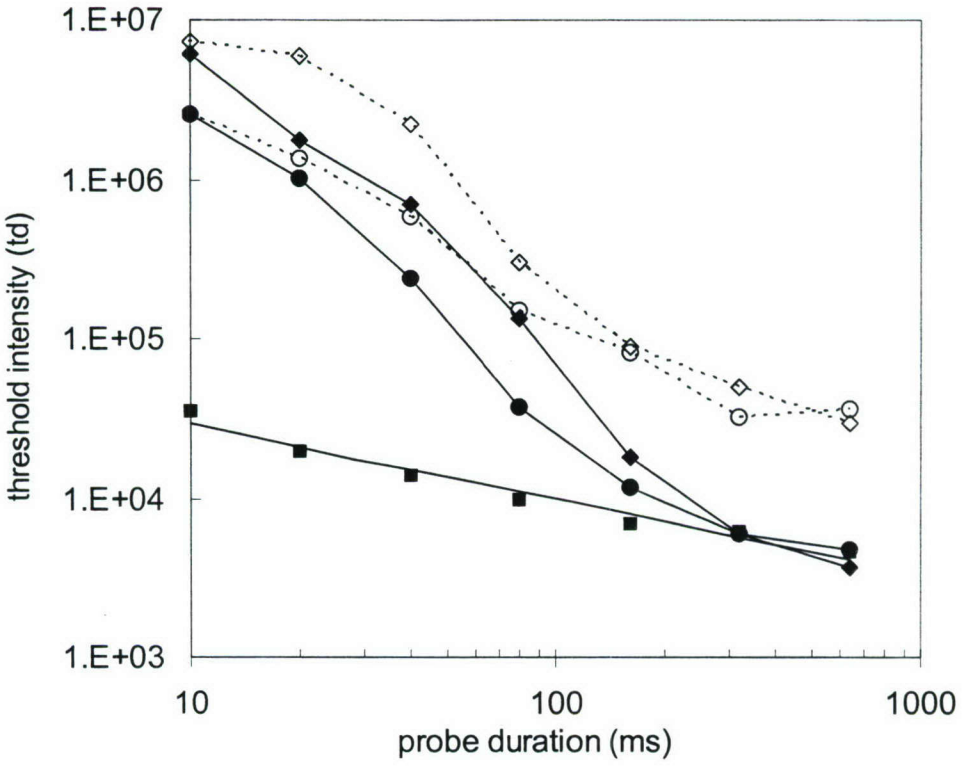

Figure 10. Experiment III: Single pulse-stretched probe. Threshold intensity for detection of single pulse-stretched probe stimuli as a function of probe duration for two adapting pulse intensities (see text for details).

3.4 Experiment IV: Multiple Pulse-Stretched Probe

The threshold intensity for detection of the multiple pulse-stretched probe stimuli after 10 ms adapting pulses is presented as a function of the probe duration in Figure 11. The solid diamonds are threshold data for 3 Hz adapting pulses, while the solid triangles are threshold data for 10 Hz adapting pulses (means of two observers). For comparison, the open symbols are the data from the multiple pulse probe experiment (Experiment I: the abscissa in this case is the probe delay). Thresholds for detection of the stretched probe stimulus against a background level equal to the level between the adapting pulses (6.0×10^4 td) are also shown (solid squares) - the line joining these points is the best fit linear regression line to the log-log data and has a slope of -0.47 ($R^2 = 0.97$).

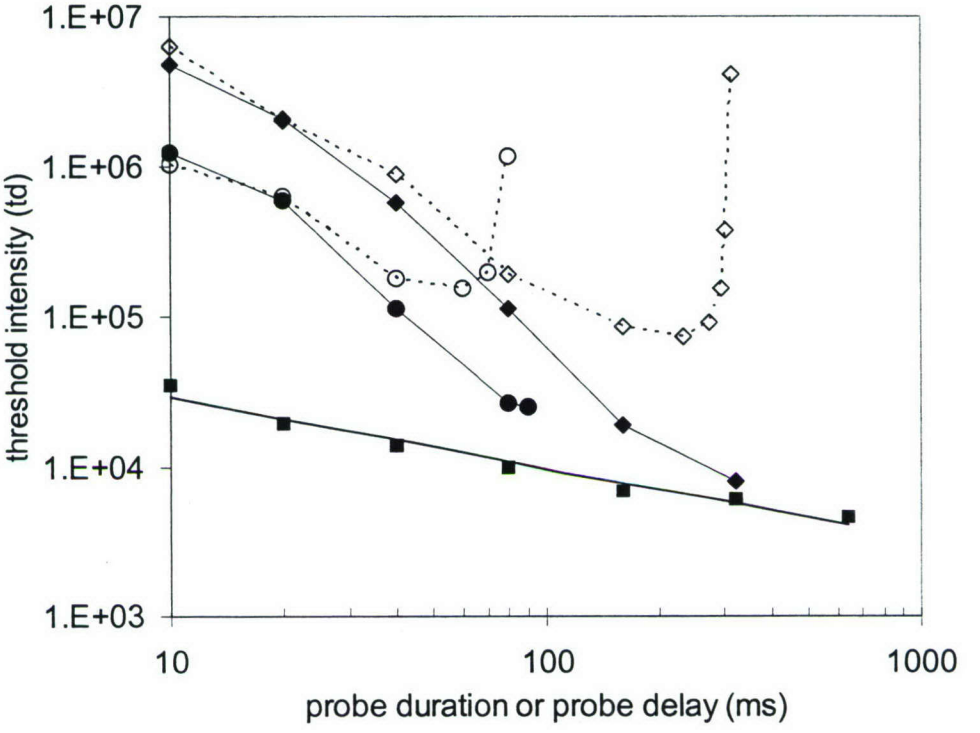

Figure 11. Experiment IV: Multiple pulse-stretched probe. Threshold intensity for detection of multiple pulse-stretched probe stimuli as a function of probe duration for two adapting pulse frequencies of equal time average intensity (see text for details).

4. DISCUSSION

Previous workers[3,13] have used a probe-sine wave paradigm to explore the dynamics of light adaptation. However, these have been at relatively low levels of illumination ($<10^3$ td). While a moderately high intensity LED stimulator has also been described previously[14], this device was limited to relatively monochromatic red LEDs. The advent of high-power, white LEDs[8] has allowed us to develop a versatile dual-channel Maxwellian view white light stimulator capable of presenting intensities of retinal illuminance over eight log-trolands with excellent stability and control.

Our first experiment measured increment thresholds during exposure to adapting pulse trains at 3 Hz and 10 Hz, using pulse durations of 1 ms and 10 ms. The pulse trains were equated for the time averaged intensity. At both pulse frequencies, forward masking processes give rise to elevated detection thresholds for the probe stimulus that decrease rapidly over the first 50-100 ms after the adapting pulse (Figure 7 and Figure 8), similar to that found by previous workers[15,16]. As the probe delay is increased, visual backward masking occurs[17], and the next adapting pulse retroactively masks the probe stimulus. Closer observation of these data reveals an asymmetry, where the duration of the forward masking phase is much longer than that of the backward masking phase.

In between these two phenomena, a minimum occurs where thresholds are lowest. For both the 3 Hz and 10 Hz trains, thresholds throughout the interval between the adapting pulses were always higher compared with those measured against a steady background with the same intensity as that presented in between the pulses in the train. This indicates that some light adaptation is maintained throughout the train. However, when compared with thresholds measured against a steady background equal to the time-averaged energy in the pulses, the probe threshold is elevated at all delay times for the 10 Hz train, whereas at 3 Hz, the minimum thresholds, measured at around 150-250 ms after the pulse, are around that of the time average case. Thus at the lower temporal frequency, recovery in between the pulses is more complete than at the higher temporal frequency.

Although there are some slight, but systematic, differences between the equal energy pulses at 1 ms and 10 ms; thresholds at long delays appear a little higher for the longer pulses. However, these differences are not great, indicating that there is reciprocity of intensity and duration; the two lights of equal energies but different durations have the same effect on sensitivity. To reduce the data collection burden in Experiments II, III and IV only 10 ms adapting pulses were used – we would expect there to be very little difference were we to have used 1 ms pulses.

In Experiment II, single pulse-probe sequences were used in place of the multiple pulse-probe sequences used in Experiment I. Two pulse energies were chosen; these were the same energies as those in the individual pulses in the trains in the first experiment. This enables a direct comparison of the response to a single pulse to that when the same pulse is presented in a train, and allows us to examine adaptation responses beyond the time when the next pulse would be arriving in the pulse trains (Figure 9).

An examination of the data from Experiments I and II show that the forward masking effect of the adapting pulses of the higher energy pulse (Figure 9; diamonds) is greater than that for the lower energy pulse (Figure 9; circles), as would be expected from early studies of

afterimages and flashblindness[18-21]. Also, compared to when pulses of the same energy are presented in a train, early thresholds for the single pulses (in the first 60 ms or so) are elevated (Figure 9; open symbols). These differences are more apparent at 10 Hz than at 3 Hz, due to the higher level of light adaptation induced by the higher frequency pulses. This occurs despite the average energy in the pulse trains being identical. Late thresholds are the same as those measured during the pulse train, and for the single pulses, recover to baseline levels (i.e. to those measured with no adapting pulses) after 700 ms, indicating that recovery is complete within this time frame.

Our intent with Experiment III was to use single pulse exposures again, and to compare threshold elevations determined by varying the duration of the probe stimulus with those determined by varying the delay of a 10 ms probe stimulus, as in Experiment II. Control thresholds for detection of the probe stimulus deviate from Bloch's Law[22] and show an inverse square root dependency on the pulse duration over 10-700 ms, indicating incomplete temporal summation (Figure 10; square symbols). Again, the forward masking effect of the adapting pulses is less for the lower energy pulses.

As the duration of the probe is increased, thresholds are much lower than those for 10 ms probe stimuli (Figure 10; open symbols are elevated compared to closed symbols), indicating that, through temporal integration, the early portion of the probe stimulus makes a contribution to the detection of the stimulus. After ~500 ms, recovery is complete for both pulse intensities, and thresholds return to control levels. The thresholds for the longer probe stimuli are lower compared to the 10 ms probe stimuli because they contain more energy. However, a parallel displacement is observed for probe durations from 20 ms to 80 ms, showing that the early rate of recovery and temporal summation have the same dependence on time after the pulse and the stimulus duration respectively. Beyond 80 ms the 10 ms probe stimuli asymptote to the no-pulse, 10 ms control level, whereas the longer duration probe stimuli keep falling to the corresponding stretched-probe control values. This is because for the lower intensity adapting flash, requiring less recovery is required, and thresholds return to baseline levels quicker.

In the final experiment (Experiment IV), the stretch probe paradigm was employed with multiple pulse exposures. The most striking feature in the results of this experiment is the disappearance of the backward masking effect seen with the 10 ms probe data (Figure 11). Since the backward masking effect is confined to a period of around 100 ms before the adapting pulse, the portion of the stretched probe presented prior to this period is detected by the observer. However, since detection thresholds for the stretched pulses decline through the backward masking "window", the latter part of the probe stimulus must also contribute to the detection process. One explanation could be that the mechanism responsible for detecting the brief stimuli differs from that for the longer stimuli; the former mechanism is susceptible to backward masking, while the latter is not.

In summary, we have modified the probe-sinewave paradigm to a pulse-probe technique. We have shown how this technique has the potential for extremely elegant determination of the adaptive state of the visual system in response to pulsed stimuli, including the investigation of temporal adaptation mechanisms. We have used very high intensity white LEDs to investigate the adaptive state of the visual system in between pulses from a flickering background, and have demonstrated forward and backward masking. Our future

intentions are to investigate the detailed shape of the probe-threshold curve as a function of pulse energy and frequency, and to develop additional data sets against which existing computational models of light adaptation dynamics[23] can be tested.

5. ACKNOWLEDGEMENTS

The authors would like to thank Dr John Taboada who built the Maxwellian view light stimulator, and Drs Bill Kosnik, Tom Kuyk, Willard Larkin and Leon McLin for useful discussions. This work was sponsored by the Air Force Office of Scientific Research and the Air Force Research Laboratory under contract number F41624-02-D-7003.

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